

# **Uncertainty of the Thermal Diffusivity Measurement Using the Laser Flash Method<sup>1</sup>**

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## **ABSTRACT**

The paper deals with uncertainty analysis of the thermal diffusivity measurement using the laser flash method. It carried out a general metrological characterization of the high temperature thermal diffusivity measurement apparatus. The metrological investigation follows general rules for evaluating and expressing uncertainty in measurement.

The work presents a brief introduction into the flash method. It summarizes the main disturbing phenomena that may significantly influence the accuracy of the thermal diffusivity measurement. It gives detailed description of the high temperature laser flash experimental apparatus installed in Austrian Research Centers. The paper gives also results of the test measurement of the thermal diffusivity of the standard materials - the austenitic steel X10NiCrMoTiB1515 in the temperature range from 20 °C to 1000 °C. The results are compared with the literature data and discussed.

Sources of measurement errors are analyzed; components of uncertainty are here categorized according to the method used to evaluate them. The results are subjected to rigorous statistical evaluation, to determine the uncertainty associated with the thermal diffusivity measurements.

**KEY WORDS:** flash method; thermal diffusivity; uncertainty analysis

## **1. INTRODUCTION**

A rather quite significant dispersion of results is the specific feature of measurement of the thermophysical properties even for well-defined solid materials. The current demand for accurate and reliable results has led to understanding of the importance of standardization of experimental methods and development of standard materials giving reliable reference data in a wide range of experimental conditions.

The laser flash method [1] of measuring the thermal diffusivity has worldwide become the most popular experimental method. The simplicity and the efficiency of the measurement, the accuracy and the reliability of results and possibilities of application under a wide range of experimental conditions and materials are the main advantages of the flash method. The fact that the flash method has received standard status in many countries acknowledges its universality. The theory, operating principles, experimental aspects and experimental data evaluation have been described in the wide amount of scientific papers and reports (see review papers [2-6]).

The ARC Seibersdorf research GmbH uses the home-made laser flash experimental apparatus that has been continuously technically developed since its installation. To fulfill the current advanced requirements and in order to fulfill the internationally accepted procedures and standards the attention has been focused to uncertainty analyses and metrological investigation.

The paper presents results of analyses of the reliability of the thermal diffusivity measurement evaluating quantitative statement of the uncertainty. The analyses follow general rules for evaluating and expressing uncertainty in measurement, established as the GUM method (Guide to the Expression of Uncertainty in Measurement) - the method that has been adopted by various regional metrology and related organizations worldwide [7-9]. The GUM approach has been followed in expressing the uncertainty of an estimation of several thermophysical properties including thermal conductivity using the transient hot strip technique [10] or the guarded hot plate technique [11] as well using the transient hot wire method [12,13]. Measurement of the thermal diffusivity using the laser flash method was metrological evaluated [14,15], the uncertainty was systematically analyzed and expressed for different laser flash equipment following the GUM recommendations, too [16].

## **2. FLASH METHOD**

In the flash method the front face of a small wall-shaped sample receives a pulse of radiant energy coming either from a laser, or a flash lamp. The thermal diffusivity value is computed from the resulting temperature response on the opposite (rear) face of the sample. The simple ideal analytical model of the flash method is based on the thermal behavior of a homogeneous opaque thermally insulated infinite slab uniformly subjected to a short heat pulse of radiant energy over its surface. The model assumes:

- a) the sample is homogeneous and isotropic, and the thermophysical properties and the density are uniform, constant and invariant with temperature within the experimental conditions,
- b) the sample is thermally insulated – there are no heat losses from the slab surfaces,
- c) the heat pulse is uniformly distributed over the slab surface, and it is absorbed by a layer of material which is very thin in comparison to the thickness of the sample,
- d) the heat pulse is instantaneous, its duration is negligible compared to the thermal response of the slab.

The one-dimensional heat flow occurs across the slab under these assumptions. The shape of the rear face temperature rise curve contains the information about the thermal diffusivity of the material. The conventional way to calculate the thermal diffusivity from the experimental data is that proposed by Parker et al [1]. The method is rather simple - by specifying the half time  $t_{0.5}$  – the time in which the rear face temperature rise reaches one half of its maximum value - the thermal diffusivity is calculated from the expression

$$a = 0.1388 \frac{e^2}{t_{0.5}}, \quad (1)$$

where  $e$  is the sample thickness.

Several other original data reduction methods (the algorithm for computing the thermal diffusivity from experimental data) in the flash method have appeared in the literature so far. They differ either in the analytical mathematical models used, or in the way the measured experimental rear face temperature vs. time data by theoretical curve, are respectively compared. The survey of the existing data reduction methods can be found elsewhere [17].

### 3. UNCERTAINTY OF MEASUREMENT RESULTS

Every measurement is affected by measurement errors that cause the difference between the measured value of the estimated property - the thermal conductivity and its true value. The true value associated with the measured property is an idealized notion, which can not be determined. It is only an approximation or an estimate of the value subjected to the measurement [7-9].

The uncertainty of the result of a measurement generally consists of several components, which may be accordingly to the GUM method grouped into two categories according to the method used to estimate their numerical values:

Type A standard uncertainties are evaluated by the statistical analysis of a series of observations. An evaluation may be based on any valid statistical method for treating data, i.e. calculating the standard deviation of the mean of a series of independent observations; using the method of least squares to fit a curve to data in order to estimate the parameters of the curve and their standard deviations; and then carrying out an analysis of variance in order to identify and quantify random effects in certain kinds of measurements.

A Type B evaluation of standard uncertainty is usually based on scientific judgment using all the available relevant information, which may include previous measurement data; experience with, or general knowledge of; the behavior and property of relevant materials and instruments; manufacturer's specifications; data provided in calibration and other reports; and uncertainties assigned to reference data taken from handbooks.

Each component of uncertainty is represented by an estimated standard deviation -the standard uncertainty  $u_i$ , and equal to the positive square root of the estimated variance  $u_i^2$ .

An uncertainty component obtained by a Type A evaluation is represented by a statistically estimated standard deviation, equal to the positive square root of the statistically estimated variance and the associated number of degrees of freedom.

In a similar manner, an uncertainty component obtained by a Type B evaluation is represented by a quantity  $u_j$ , which may be considered an approximation to the corresponding standard deviation; it is equal to the positive square root of  $u_j^2$ . It may be considered an approximation to the corresponding variance and obtained from an assumed probability distribution based on all the available information. Since the quantity  $u_j^2$  is treated like a variance and  $u_j$  like a standard deviation, for such a component the standard uncertainty is simply  $u_j$ .

All the individual uncertainties influence the uncertainty of the result measurement. The combined standard uncertainty  $u_c$  represents the estimated standard deviation of the result. It is obtained by combining the individual standard uncertainties  $u_i$  arising from a Type A or a Type B evaluation, using the usual method for combining standard deviations based on the law of propagation of uncertainty. Multiplying the combined uncertainty with a coverage factor  $k$  ( $k$  is typically in the range 2 to 3) one receives expanded uncertainty  $U$ . It is confidently believed that measurand  $Y$  (the true value of the thermal conductivity) is greater than or equal to  $y - U$ , and is less than or equal to  $y + U$  (i.e.  $Y = y \pm U$ ), where  $y$  is the measured value of the estimated property - the thermal conductivity. When the normal distribution applies  $U=2u_c$  (i.e.,  $k=2$ ) defines an interval having a level of confidence of approximately 95%, and  $U = 3 u_c$  (i.e.,  $k=3$ ) defines an interval having a level of confidence greater than 99%.

#### 4. EXPERIMENTAL APPARATUS

The laser flash apparatus is regularly used for measurements of the thermal diffusivity of solids at the Materials Research Division of the Austrian Research Centre in Seibersdorf. It consists of Nd:Cr:GGG (galium-gadolinium garnet doped with neodymium) glass laser (BLS400, Baasel Lasertech) working at wave length  $\lambda = 1.064 \mu\text{m}$  with the justified pulse energy up to  $10 \text{ J.cm}^{-2}$ . The pulse energy is usually set to  $5 - 6 \text{ J.cm}^{-2}$  in order to keep the sample temperature rise below  $3^\circ\text{C}$ . The transient temperature is measured by the liquid nitrogen cooled HgCdTe infrared detector (HCT-80, Infrared Associated, Inc.) with preamplifier (PPA-15-DC). The detector has a time constant of about 300 ns and is set to detect radiation from the central square area ( $\sim 4 \text{ mm}^2$ ) at the sample rear face. The sample is supported in a horizontal position in the vacuum chamber. A short tantalum tube acts as the resistance heater and allows measurements in the temperature range from 20 up to  $1900^\circ\text{C}$ . The furnace is powered by a DC current from the power source (TN 10-5000, Heinzinger Elektronik). The sample temperature sensor consists of the steel encapsulated K-type (NiCr/Ni) thermocouple of 1 mm in diameter, or spot-welded S-type (Pt/PtRh10) thermocouple made from wires of 0.35 mm in diameter (Heraeus). All data acquisition and control is performed using the standard measurement hardware and PC computer.

The apparatus is constructed along two axes (Fig. 1). The laser is placed horizontally. The laser beam is reflected by a bending mirror and follows vertically through a glass window (BK7) into a water-cooled stainless-steel vacuum chamber. The vacuum is stabilized using the turbo pump (TPH 110, Pfeiffer Wakuumtechnik) at values of  $10^{-5}$  Pa order. The sample holder consists of three molybdenum rods that fix the sample in a horizontal position in the central zone of the furnace. The construction allows the irradiation of the lower (front) face of the sample and the measurement of temperature and temperature response on the upper (rear) face of the sample. The detachable top of the vacuum chamber fixes the IR temperature sensor that is focused with  $\text{CaF}_2$  lens and

mechanical iris. The chamber top contains the movable tubes that allow the setting and, through a window, the checking of the thermocouples' position.

## 5. THERMAL DIFFUSIVITY OF STEEL

To determine the performance characteristics and reliability of the equipment various test measurements were performed on a stable and well-characterized specimen. The austenitic steel X10NiCrMoTiB1515 (Nr.1.4970) - a material that had been intensively investigated by German Thermophysical Society [18], has been chosen for the experimental investigation. The composition of the material fully conforms to the DIN (Table I). All the measurements were performed in the vacuum.

Table II and Figure 2 present results of three different measurements of the thermal diffusivity. Here the experimental recordings are analyzed using the equation (1) applying the Clark and Taylor correction [19] for the heat loss elimination. The values  $a_1$  to  $a_3$  represents averages of these values obtained for three different measurements. Table III and Figure 3 summarize the thermal diffusivities estimates calculated using data reduction procedure proposed by Degiovanni [20]. The method takes into account of heat losses and gives three thermal diffusivity values computed using four different fractional times. The values  $a_1$  to  $a_3$  represents averages of these values obtained for three different measurements. We see, that deviations lies between  $\pm 1.3\%$  in both cases, that means, that the reproducibility of the measurement in the temperature range between the room temperature and  $900\text{ }^{\circ}\text{C}$  is better than  $1.3\%$ . Table IV summarizes these results of estimation the thermal diffusivity of the austenitic steel. Value  $a_{\text{mean}}$  is the mean value of the thermal diffusivities  $a_{01}$  and  $a_{02}$  – the average values taken from the Tables II and III,  $a_{\text{REF}}$  is the reference value taken from round-robin test measurements performed by 10 independent measurements within 6 laboratories, whose results were published in [18]. These results confirm the accuracy of the measurement better than  $1.7\%$  in the temperature range between the room temperature and  $900\text{ }^{\circ}\text{C}$ .

Table V presents results of 12 independent measurements performed on different samples. Here the thermal diffusivity  $a$  are the average values these tests performed at each temperature. Each individual thermal diffusivity value is calculated as the average of three values derived using the equation (1) applying the Clark and Taylor correction [19] applied for three different ratios of partial times. Comparison shows, that differences between the obtained thermal diffusivities and reference values are better than  $0.3\%$ . The standard deviation is lower than  $1.03\%$ . It generally decreases with an increase of the temperature. This results from an increase of the sensitivity of IR temperature detector with the temperature.

## 6. ESTIMATE OF UNCERTAINTY

Estimation of the thermal diffusivity using the flash method is based on the knowledge of the sample thickness and of the shape of the temperature rise vs. time evolution of the sample rear face. The sources of uncertainties in the measurement are therefore associated with the sample itself, the temperature measurements, the performance of the detector and the data acquisition board, the data analysis. The disturbing phenomena - the finite pulse time effect, the non-uniform heating and heat losses from the sample represent sources of uncertainties as well.

### *Type A Component of Uncertainty*

The relative standard deviation values from the Table V represent the type A uncertainties involved in this measurement process. It can be concluded that the value

1.1 % well represents the type A component of the uncertainty associated with the thermal diffusivity measurements.

#### *Type B Component of Uncertainty*

Type B components of uncertainty are estimated and discussed individually for each source of uncertainty. Values of these components are given as limits between which the particular influence quantity may generate a variation of the measured value. This means that a rectangular distribution is implicitly assumed for the occurrence probability of the values within the limits given.

#### *Sample Thickness*

The sample thickness is measured with certified micrometer with the accuracy of 0.5  $\mu\text{m}$ . For the typical 2.5 mm thick sample the relative accuracy is 0.02 %. Thermal diffusivity is related to the square of the specimen thickness and

$$\frac{\Delta a}{a} = 2 \frac{\Delta e}{e} . \quad (9.1)$$

The error limits associated with the sample thickness measurement are 0.04 %. This uncertainty is usually decreased performing repeated measurements of the sample thickness and taking the average value into account.

The material's thermal expansion during the test introduces another source of error that should be taken into account. The Table VI presents results of dilatometric measurement of the test material. Thermal expansion values for the temperature range 20 - 900°C show that maximal relative prolongation is  $\Delta L/L = 0.29 \cdot 10^{-3}$ . The error implied by not correcting the results for thermal expansion of the steel is therefore estimated to be lower than 0.06 %.

#### *Absolute Sample Temperature*

The absolute (steady state) sample temperature does not enter into the thermal diffusivity estimation. It is the temperature the achieved thermal diffusivity is being referred to. The temperature is measured using a type K thermocouple (NiCr/Ni), whose uncertainty specified by its manufacturer is 1.1 °C or 0.4 % of the measured value. The uncertainty of the thermal diffusivity estimation depends on the thermal diffusivity vs. temperature dependence of the measured material. Considering the steel thermal diffusivity vs. temperature evolution can be stated, that the uncertainty of the thermal diffusivity estimation is better than 0.4 % in the temperature range 20 - 900°C.

It should be noted, that during a thermal diffusivity experiment, the effective temperature of the sample is higher than it's steady state temperature before the (laser) heat pulse application. In the case the thermal diffusivity of the measured material significantly depends on the temperature, what is not the case for the steel measurement a special analysis should be performed [6].

The reliability of the thermal diffusivity measurement strongly depends on the level of stability of thermal equilibrium achieved within the sample before starting a measurement (before an application of the heat pulse). Constant absolute temperature at level of  $\pm 1^\circ\text{C}$  within an interval of 3-5 minutes was found to be an acceptable condition. Our experiences show, that it is very important to check the time stability of the relative temperature of the rear face. The relative temperature rise is measured with much higher temperature resolution than the absolute temperature of the sample. We found that the changes of this temperature evolution – systematic or random, dramatically influence the reliability of the measurement. That's why the sample rear

face temperature is continuously monitored on the working relative temperature measurement's resolution and with the working time scale and the measurement (heat pulse application) starts only if the required temperature stability at the desired temperature of the measurement occurs.

#### *Rear Face Temperature Evolution – Temperature Detector Inertia*

The manufacturer of the IR temperature detector specifies the time constant of 300 ns. As the typical response time is of order of tenth of second (the halftime for a 3 mm thick sample is about  $t_{0.5} = 0.1$  s from 20 to 800°C the uncertainty in the temperature measurement due to the inertia (response time) of the temperature detector is extremely small. The influence of this phenomenon on the accuracy of the thermal diffusivity measurement can be therefore neglected.

#### *Nonlinearity of the Temperature Detector*

An important factor in the measurement is to ensure that the temperature detector operates within the linear range, where the signal response of the detector (voltage) is proportional to the input radiation. This is valid for small temperature changes (smaller than 10 °C) [17]. As it comes from Planck's law nonlinearities are within this small temperature change lower than 1 % for temperatures up to 1000°C. In our measurements the rear face temperature increase is always kept below 3 °C by setting the suitable laser power that generates the heat pulse over the front face of the sample.

The nonlinearity of the preamplifiers and the analog to digital conversion represent the second source of the possible nonlinearities of the temperature measurement. Because we work the level of very small voltages The manufacturer of the preamplifier doesn't specify the its linearity. The manufacturer of the data acquisition board assures the linearity of the preamplifier at the used gain as well as linearity of the analog to digital conversion better 0.065 %.

Because the thermal diffusivity estimation is based on an analysis of the shape of the temperature rise vs. time evolution, the influence of nonlinearity of the temperature rise detection can be decreased or eliminated utilizing the “whole” temperature vs. time evolution rather than only a single point in the data reduction. Moreover the reliability of the measurement is in our measurements checked comparing the measured temperature rise vs. time evolution with the analytical curve as well as analyzing the experimental data by several data reduction procedures. In this way any potential deviation of the experimental conditions from those assumed in the analytical model can be easily identified.

We estimate that the influence of the nonlinearity of the temperature rise measurement on the accuracy of the thermal diffusivity measurement is lower than 0.5 %.

#### *Performance of the Digital Data Acquisition Board*

The manufacturer states the following characteristics of the used data acquisition board:

Signal resolution: 12 bit (1 in 4 096, or 0.02 %)

A/D conversion time: 706  $\mu$ s (at the maximal gain - 1000)

Time base accuracy: 0.015 %

Based on these characteristics, it is considered that the errors in thermal diffusivity due to the digital data acquisition board's operational errors are negligible small compared to the other error sources.

#### *Time Scale and the Time Origin*

Since the measurement of the thermal diffusivity is based on an analysis of the temperature rise vs. time evolution, the accuracy and reliability of the time scale is essential for the accuracy of the thermal diffusivity measurement. In our measurement

the time scale is derived from the 8 MHz quartz-based timer, whose stability of the time base the manufacturer states better than 0.015 %.

The time origin is measured using a fast photodetector (photodiode) that measures the laser light inside the laser cell. The photodetector has the response time of order of  $\mu\text{s}$ . The time scale is set to perform 1000 measurements a defined desired time interval. When measuring the steel, the working frequency was set to 2 kHz. We estimate that error associated with the time origin measurement is therefore 0.5 ms, i.e. the time scale may be shifted to that value. As the halftime for a 3 mm thick steel sample is about  $t_{0.5} = 0.1$  s from 20 to 900°C when evaluating the measurement using the Parker's procedure (equation 1) the error in the thermal diffusivity estimation should be lower than 0.5 %. When the thermal diffusivity is estimated using a more sophisticated data reduction methods the influence of this phenomenon should be much lower.

#### *Heat Pulse Width*

The photodetector measures the onset of the laser flash. To be in a consistency with the theory the heat pulse shape and width should be taken into account. The manufacturer states that the laser flash duration is 0.2 – 1.5 ms. To take the heat pulse width into account the time origin is shifted to the center of gravity following the procedure described in [21]. If one compares the correction time with the half time value one can see, that correcting the data for the pulse width can have an influence of 0.75%. We estimate that the influence of the heat pulse width on the accuracy of the thermal diffusivity measurement is lower than 0.1 %.

#### *Non-uniform Pulse Heating*

The uniformity of the laser beam is directly related to the uniformity of the sample's heating, and is usually a major source of error in the measurements. The manufacturer specifies homogeneity of the laser beam within the diameter of 12 mm. We use the central part of the diameter 10 mm only. To assure and check the homogeneity of the laser pulse a photographic paper is periodically exposed by the laser light. The homogeneity of the absorption surface is assured as well. Here we do not evaluate the influence of the non-uniformity of the pulse heating on the accuracy of the thermal diffusivity measurement.

#### *Heat Losses*

To eliminate heat losses several improvements of the sample holder and experimental cell were introduced to eliminate the phenomenon experimentally as much as possible. Anyway heat loss between the sample and the environment cannot be neglected. That's why we utilize the data reduction methods that account of heat losses. Agreement amongst thermal diffusivity values obtained using different data reduction methods assures the reliability of the measurement. Taking account of the results from the Table II and 3 we estimate that the influence of heat losses on the accuracy of the thermal diffusivity measurement is lower than 1.3 %.

Table VII summarizes the estimates of the uncertainties accordingly to their type and sources. As we suppose uniform (rectangular) distribution the corresponding individual standard deviations can be calculated from the equation

$$u_j = a/\sqrt{3} \quad , \quad (2)$$

where  $a = (a_+ - a_-)/2$ ,  $a_+$  and  $a_-$  are the estimated upper and lower limits.

Since we suppose that there is no correlation between phenomena that represent the sources of uncertainties, the B type component of the uncertainty in the thermal

diffusivity measurement can be calculated as the square root of the sum of the squares of the individual standard deviation values. This leads to 0.79 % type B uncertainty associated with the experiments. The combined standard uncertainty is calculated similarly from the type A and B components. With 1.1 % type A uncertainty, the combined standard uncertainty becomes 2.89 %. The expanded uncertainty gives then the value 3.78 % within 95 % confidence level.

## **7. CONCLUSIONS**

This paper presents results of an uncertainty analyses of the thermal diffusivity measurement using the laser flash method apparatus installed in the ARC Seibersdorf research GmbH through a series of tests measurement performed on austenitic steel X10NiCrMoTiB1515 (Nr.1.4970). It is concluded that the expanded uncertainty associated with the thermal diffusivity measurement in the temperature range 20 to 900°C is 3.78 % within 95 % confidence level.

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## TABLES

Table I Chemical composition of the austenitic steel X10NiCrMoTiB1515  
(Nr.1.4970)

<i>element</i>	<i>weight %</i>
C	0.09
Si	0.45
Mn	1.7
P	0.003
S	0.004
Cr	14.6
Ni	15.0
Mo	1.25
Ti	0.46
Cu	0.07
B	0.0015
Al	<0.006

Table II Thermal diffusivity of steel calculated using the equation (1) and correction [19]

$T$ /°C	<i>Thermal diffusivity</i> /10 <sup>-6</sup> *m <sup>2</sup> /s			<i>Mean</i> /10 <sup>-6</sup> *m <sup>2</sup> /s	<i>Standard deviation</i>	
	$a_1$	$a_2$	$a_3$	$a_0$	+/-	%
30	3.53	3.57	3.52	3.54	0.024	0.69
100	3.74	3.79	3.69	3.74	0.048	1.28
200	3.98	3.91	3.96	3.95	0.033	0.84
300	4.18	4.18	4.23	4.20	0.029	0.69
400	4.41	4.45	4.45	4.44	0.019	0.44
500	4.66	4.69	4.67	4.67	0.020	0.42
600	4.90	4.95	4.96	4.94	0.034	0.68
700	5.03	5.02	5.07	5.04	0.026	0.52
800	5.34	5.33	5.34	5.33	0.006	0.10
900	5.47	5.51	5.51	5.49	0.025	0.46

Table III Thermal diffusivity of steel calculated using the data reduction method [20]

$T$ /°C	<i>Thermal difusivity</i> / $10^{-6}$ * m <sup>2</sup> /s			<i>Mean</i> / $10^{-6}$ * m <sup>2</sup> /s	<i>Standard deviation</i>	
	$a_1$	$a_2$	$a_3$	$a_0$	+/-	%
30	3.54	3.56	3.62	3.57	0.038	1.05
100	3.77	3.80	3.77	3.78	0.017	0.46
200	3.93	3.94	3.96	3.94	0.016	0.39
300	4.27	4.22	4.24	4.24	0.023	0.53
400	4.42	4.44	4.47	4.44	0.026	0.59
500	4.68	4.65	4.68	4.67	0.016	0.35
600	4.88	4.99	4.95	4.94	0.054	1.10
700	5.02	5.02	5.13	5.05	0.061	1.21
800	5.24	5.27	5.36	5.29	0.061	1.16
900	5.45	5.48	5.46	5.46	0.017	0.30

Table IV Thermal diffusivity of steel. Comparison of measured values and reference data.

$T$ / °C	<i>Thermal difusivity</i> /10 <sup>-6</sup> * m <sup>2</sup> /s				<i>Standard deviation</i>	
	$a_{01}$	$a_{02}$	$a_{\text{mean}}$	$a_{\text{REF}}$	+/-	%
30	3.54	3.57	3.56	3.57	-0.013	-0.37
100	3.74	3.78	3.76	3.75	0.009	0.24
200	3.95	3.94	3.95	3.99	-0.045	-1.13
300	4.20	4.24	4.22	4.24	-0.021	-0.50
400	4.44	4.44	4.44	4.48	-0.042	-0.95
500	4.67	4.67	4.67	4.73	-0.058	-1.24
600	4.94	4.94	4.94	4.98	-0.042	-0.85
700	5.04	5.05	5.05	5.10	-0.054	-1.06
800	5.33	5.29	5.31	5.33	-0.018	-0.34
900	5.49	5.46	5.48	5.57	-0.092	-1.67

Table V Thermal diffusivity of steel. Comparison of measured values and reference data.

$T$  /°C	<i>Thermal difusivity</i>					
	$a$	stdev	stdev/ $a$	$a_{\text{REF}}$	$a_{\text{REF}} - a$	$(a_{\text{REF}} - a) / a_{\text{REF}}$
	/10 <sup>-6</sup> * m <sup>2</sup> /s	+/- 10 <sup>-6</sup> * m <sup>2</sup> /s	%	/10 <sup>-6</sup> * m <sup>2</sup> /s	+/- 10 <sup>-6</sup> * m <sup>2</sup> /s	%
30	3.56	0.037	1.03	3.57	-0.011	-0.30
100	3.75	0.038	1.02	3.75	-0.002	-0.04
200	3.99	0.042	1.04	3.99	-0.001	-0.03
300	4.23	0.038	0.89	4.24	-0.013	-0.30
400	4.48	0.034	0.76	4.48	-0.004	-0.09
500	4.72	0.026	0.55	4.73	-0.013	-0.27
600	4.99	0.023	0.47	4.98	0.005	0.10
700	5.11	0.031	0.61	5.1	0.012	0.24
800	5.34	0.049	0.92	5.33	0.014	0.26
900	5.55	0.031	0.56	5.57	-0.018	-0.33

Table VI Thermal expansion of the austenitic steel X10NiCrMoTiB1515  
(Nr.1.4970)

$T$ / $^{\circ}C$	$\Delta L/L$ $10^{-3}$
50	0.008
75	0.018
100	0.020
125	0.024
150	0.030
175	0.037
200	0.042
225	0.047
250	0.053
270	0.058
300	0.065
350	0.077
400	0.095
450	0.122
500	0.157
550	0.186
600	0.219
650	0.254
700	0.280
750	0.288
800	0.285
850	0.247
900	0.256

Table VII Sources of uncertainties and standard deviations

<i>Type of Uncertainty</i>	<i>Source of Uncertainty</i>	<i>Uncertainty Limits / %</i>	<i>Standard Deviation / %</i>	
A	Random		1.1	1.1 %
	Sample thickness	0.04	0.023	
	Sample thermal expansion	0.06	0.035	
	Absolute sample temperature	0.4	0.231	
	Temperature detector inertia	0	0	
B	Nonlinearity of the temperature detector	0.5	0.289	0.79
	Performance of the digital data acquisition board	0	0	
	Time scale and the time origin	0.5	0.289	
	Heat pulse width	0.1	0.058	
	Nonuniform pulse heating	x		
	Heat losses	1.3	0.751	

## CAPTIONS TO FIGURES

Fig. 1 Schematic view of the experimental apparatus (TC - thermocouple, IRD - infrared detector, PA - preamplifier, L - lens, S - sample, H - heater, W - window, VCH - vacuum chamber, M - mirror, PS - power source, PC - personal computer, CU - controller unit)

Fig. 2 Thermal diffusivity of steel. Comparison of measured values ( $a_{\text{aver}}$ ) and reference data ( $a_{\text{REF}}$ )

FIGURES

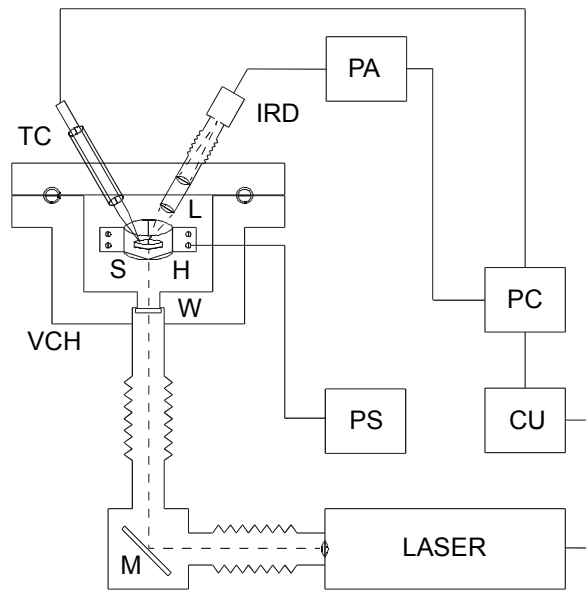


Fig. 1

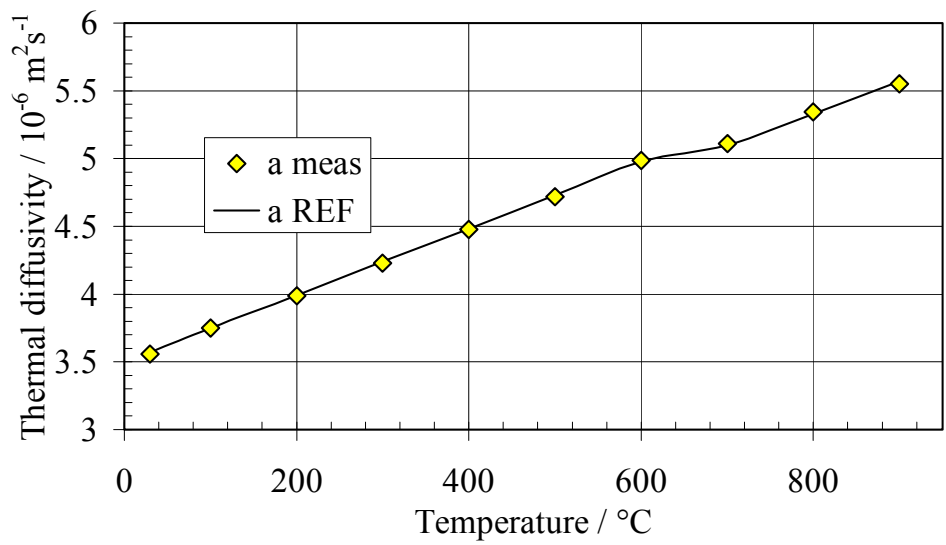


Fig. 2